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Acoustical characterization of touristic caves in Portugal

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Since the Paleolithic, Mankind has been taking advantage of the acoustical characteristics of natural caves to perform its rituals. Nowadays many of these spaces are used as touristic attractions or even as stages for musical performances. This study characterizes three touristic caves in Portugal where in situ measurements were done, of background noise sound pressure levels, RASTI and Reverberation Time. The average RT values were 1.3 s to 1.7 s and the RASTI average values revealed good intelligibility (from 0.50 to 0.57). The sound absorption coefficient of the stone that constitutes the interior of those caves was also measured in a standing wave apparatus.

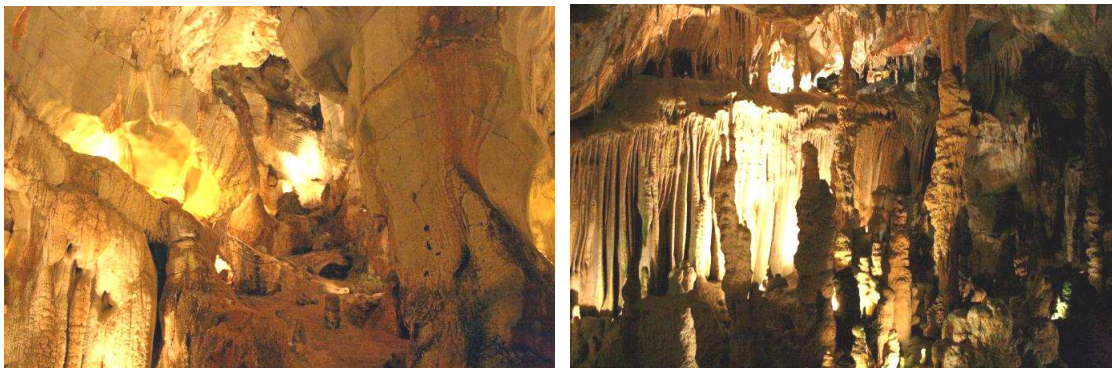


1 - INTRODUCTION

Mankind has been occupying caves since Eras as distant as the Paleolithic. The capability of intensifying and modifying sound as desired has been perhaps one of the characteristics that determined the preference for certain caves since those days. Nowadays, many caves are visited for touristic purposes, for their beauty and their geological interest, but also as places for celebrations and musical concerts or even as religious temples. Considering these uses, it is important to determine if these places are acoustically suitable for the different activities that occur in them [1-3].

2 – THE SAMPLE

The three caves studied in this investigation (*“Grutas da Moeda”* - Coin Caves, *“Grutas de Santo António”* - Saint Anthony Caves and *“Grutas de Alvados”* - Alvados caves) are located in the mountains of Aire and Candeeiros, in the central region of Portugal, within the same important mass of limestone called *“Maciço Calcário Estremenho”*, dated from the Jurassic period (fig. 1 and 2). All of these caves are open to the public for touristic visits, occasionally working as a stage for some musical performances. They are geologically very similar. The permeability of these limestone masses is due to the frequent presence of cracks in fractures and joints in the mass that lead to a quick infiltration to deep levels of the water in the soil, originating phenomena as karst erosion, which is the result of the water dissolving the limestone. This water, as it flows through the surfaces, transporting and depositing calcite particles, originates complex and compact surfaces, with stalactites, stalagmites, and other formations.



Figures 1 and 2 – *“Sala do Pastor”* (Room of the Shepherd) and *“Cascata”* (Waterfall) (Moeda Caves) [left] and *“Grande Sala”* (Large Room) (Santo António Caves) [right].

The *Moeda Caves* are a complex of different rooms that are connected as if that were a tunnel, all of them profusely filled with karst formations. There is a wider space (the *Cascata*, "waterfall", fig. 1) where there have been some musical performances in the past, which is why the acoustic measurements were done there.

The *Santo António Caves* are a set of two rooms connected by a natural tunnel. The room which was studied, *Grande Sala* ("Large Room"), is a big chamber with great density of stalactites, stalagmites, columns and curtains (fig. 2), where musical concerts take place occasionally.

The *Alvados Caves* are also a complex of different rooms connected by natural and artificial tunnels that have been altered in order to accommodate the touristic visits, which is why the karst

formations are more present in some of the rooms than in others. In the rooms that were not altered, one can observe a certain verticality of the surfaces, making the deposits of calcite more disperse and the rooms more regular than on the other caves studied.

The interior soundscape of these caves is altered seasonally, as the frequent and abundant rain during winter infiltrates the soil into the caves, creating a constant noise provoked by the flow of the water, whilst during summer these infiltrations are considerably reduced, causing the noise level to drop.

The three spaces studied are very different in terms of their morphology, concerning their volume (table 1) and their shape as well as type of surfaces and karst formations. This last point is really different from space to space. In the *Moeda Caves* there is a clear tunnel formation, whilst in *Santo António* the space studied is a wide open room, strongly occupied by karst formations, and *Alvados* has multiple wide spaces, but each one is considerably smaller and less occupied by formations.

Table 1 – Approximated values of the area and volume of the spaces studied [4].

Room (Cave)	<i>Moeda</i>	<i>Santo António</i>	<i>Alvados</i>
Area (m ²) approximate	476	1382	198
Volume (m ³) approximate	2930	8640	1350

3 – REVERBERATION TIME

3.1 - Methodology

The reverberation time (RT) was measured using a *B&K 4224* sound source and a *B&K 2260* sound level meter, using five or six different locations in each cave (making two measurements in each location). The mean values obtained for the RT in each frequency band are shown in figure 3 [4].

3.2 - Results

In the *Moeda Caves* the mean RT [500, 1k Hz octave bands] is 1.3 s. Considering the rigidity and compactness of the surrounding surfaces and the volume of the room, that value appears to be unexpectedly low. However, a thorough analysis allows to understand that the roughness and irregularity of all the surfaces, with their complex shapes, including various concavities, protuberances, and tunnels, are responsible for a large loss of energy of the sound waves, since they cause a great diffusion and confinement of the sound waves until they are no longer audible. These irregularities are also responsible for a huge absorption area, which, although the material has a low absorption capacity, allows for an effect of considerable significance. All this causes a low RT. Figure 3 shows that RT values are higher in low frequencies. This happens partly because low frequency sound waves find it more difficult to penetrate deeply in confined spaces, which does not happen to medium and high frequency sounds waves, causing the former to stay in the measurement rooms for longer. The values for the range above 1 kHz are also affected by the air absorption.

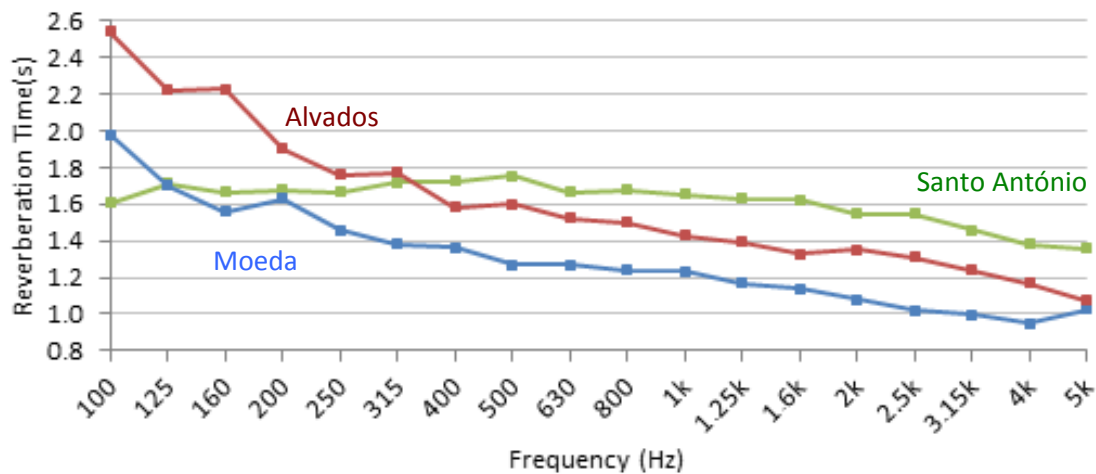


Figure 3 – RT mean values in 1/3 octave frequency bands, in the three caves main rooms.

In *Santo António Caves* the mean RT [500,1k Hz] is 1.7 s and the RT for each frequency band is relatively constant (figure 3). These values are low considering the large volume of the room studied. The room is wide, but has many protuberances and concavities of different dimensions and very irregular surfaces, causing the sound to lose a lot of energy in those formations. Thus, the reflections have a low level of energy and the measured RT is low. The effect of the huge surface area absorbing the sound is also felt in this room. Once again, the sound in high frequencies is more affected by the air absorption and the loss of energy in the karst formations.

The values measured in the *Alvados Caves* lead to a mean RT [500,1k] of 1.5 s. Once again, this value is low due to the absorption of energy by the irregular surfaces and the considerable area of the surroundings, and also due to the existence of four passage ways to other rooms that cause the sound to escape the space studied. Figure 3 shows that the RT values descend almost continuously from 100 to 5k Hz, with a difference of 1.4 s between equivalent RTs. The room studied is a wide space, with an approximately regular shape, where the floor and the ceiling are almost parallel, as well as the walls. The surfaces are rough, but have few formations, protuberances or concavities of considerable dimensions. Thus, there is no way to quickly dissipate the energy of low frequency sound waves, whereas the high frequencies are more easily absorbed by the small karst formations and by the air in the room.

3.3 - Results comparison

The highest RT values are found in the *Santo António Caves* (except in low frequencies), the caves where the space studied was the biggest (more than three times the volume of *Cascata*, in *Moeda Caves*, and six times the volume of the room studied in *Alvados caves*). The effect of volume is the main responsible for the highest RT values, overcoming the absorption effect of the complex surfaces. Although more evident in *Santo António Caves*, the sound absorption of the surfaces is not enough to overcome the effect of the volume.

The fitting curve to the mean RT values [500, 1k Hz octave bands] according to the correspondent volume V (m^3) is:

$$RT = 3.83^{-5} V + 1.32 \quad (R^2 = 0.47) \quad (1)$$

This means that 47% of the mean RT variation can be explained through the variation in volume of the rooms. This equation (1) may be used with caution to other similar caves as a first RT approximation.

The comparison between *Moeda* and *Alvados* proves that the increase in volume does not necessarily imply the increase in RT, probably due to the very different configuration of the rooms: *Moeda* caves have an intricate structure, with voluminous spaces and very irregular surfaces; *Alvados* is constituted by wide regular shaped rooms, without big deformations on its surfaces. Therefore, the sound waves suffer much more dissipation and loss of energy in the first caves. Also, the ratio between the surrounding absorption area and the volume is much larger in *Moeda* than in *Alvados*, which causes the sound absorption by the material to occur in a greater scale in the first caves. It is possible to affirm that the roughness of the surfaces and the morphology of the caves play a crucial role in their acoustic behavior. The more intricate the morphology of the space and the more complex the surrounding surfaces, the lower the RT will be, due to the increase in the equivalent sound absorption.

4 – BACKGROUND NOISE

4.1 - Methodology

The measurements of the equivalent continuous sound pressure levels (L_{eq}) of the background noise was done in rainy periods and in dry weather, using a B&K 2260 and a B&K 2236 sound level meters), in 10 minute periods [4].

4.2 - *Moeda* caves

The measurements of the background noise sound pressure level in a rainy period were done in *Sala do Pastor* ("Shepherd room"), in a central point of the biggest room of the caves (above the *Cascata*- "waterfall", but within the same room), where the influence of the sound of the waterfall does not overpower the background noise. The sound pressure level was measured in three distinct moments, always without visitors:

- with the artificial Waterfall flowing and the background Music (*WM* scenario);
- with only the background Music (*M* scenario);
- without any of the Sound sources (*nS* scenario).

It is important to note that, as the waterfall was on during the first measurements, it still had some influence on the subsequent scenarios as it had increased the amount of water flowing through the cave and consequently the noise registered, even after it had been turned off. By applying the A filter to the results obtained, the results were a LA_{eq} of 63 dB to *WM* situation (fig. 4), 52 dB to *M* situation and 40 dB for the *nS* situation (fig. 5).

The measurements in dry weather were made in a room called *Marítima*, where there have been some musical and theatre performances in the past. It was chosen due to the unwanted presence of a constant water flow in the other rooms (*Cascata* and *Sala do Pastor*). This measurement, with no equipment turned on and no visitors, obtained the results which are shown in table 2. Even these values were somewhat influenced by the artificial waterfalls, since they were turned on just a few minutes prior to the measurements. Even in that condition, the registered L_{eq} is remarkably low (< 25 dB), so is it possible to say that this space is really silent. During 10% of the measurement time the sound level was below 20 dB(A) and during 50% of the time it was

below 21 dB(A). With a LA_{eq} of 40 dB in rainy weather with no equipment turned on and a LA_{eq} of 23 dB in dry weather in the same situation, it is possible to affirm that the water flow has a huge influence in the acoustics of this space, being responsible for a variation of more than 17 dB in the measured LA_{eq} .

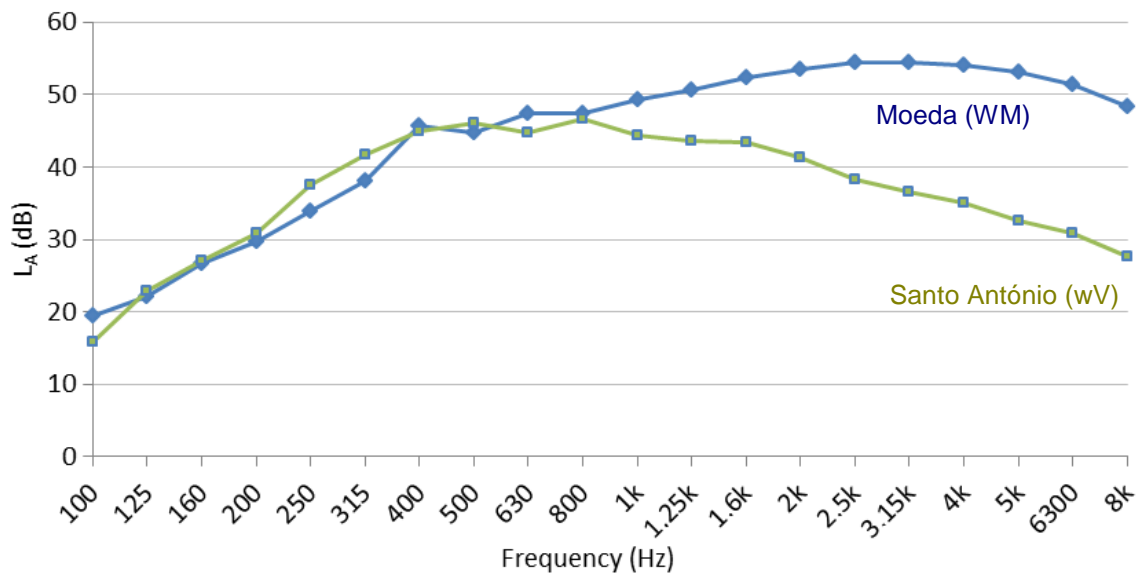


Figure 4 – Background noise sound levels, L_A (dB), in the Moeda Caves in the WM scenario (Waterfall+Music) and in the Santo António Caves in wV scenario (with Visitors).

Table 2 – Background noise sound levels in the caves, measured in dry weather (without any activities or equipments) and in rainy period (noise resulting only from the water flow naturally).

Cave	LA_{eq} (dB)			LA_{10} (dB)	LA_{50} (dB)	LA_{90} (dB)
	Dry	Rainy	Δ (=D-R)	Dry	Dry	Dry
Moeda	23.1	40.3	17.2	25.0	21.0	20.0
Santo António	21.6	32.7	11.1	24.0	20.5	<20.0
Alvados	-	32.4	-	-	-	-

4.3 - Santo António Caves

The location chosen for the measurements was picked in an attempt to reduce the influence of the sound of water drops inside the cave by choosing the location where the space was wider and the ceilings were the highest.

In *Santo António Caves* the sound pressure level measured in rainy weather was obtained in two different scenarios: with visitors during a guided tour of a group of approximately ten people going through the *Grande Sala* (wV scenario); and during a period with no visitors (nV). The results were a LA_{eq} of 54 dB to the wV scenario (fig. 4) and of 33 dB to the nV scenario (fig. 5). The effect of visitors in the LA_{eq} is evident, increasing the value in about 21 dB. When analyzing the results without visitors, the higher sound level in the higher frequencies is due to the sound of the falling water drops on the cave's pavement and on top of the different equipment existent in the cave.

In dry weather, the results obtained prove how silent this type of spaces can be (table 2), with a LA_{eq} of 21.6 dB, a LA_{10} of 24 dB and a LA_{90} below 20 dB, which are values hardly ever obtained outside reverberant or anechoic chambers. Therefore, it is possible to say that these are one of the most silent natural spaces, even with the permanent interference of the water flow, of air movement, and possibly of some fauna living on the cave.

4.4 - Alvados Caves

In *Alvados Caves*, the measurements were done during the rainy period, on a central location in the space studied, trying to minimize the effects of the sound of water drops and infiltrations in the walls. These caves are only open to the public during summer and do not have any equipment besides the lighting (which can cause background noise), so the background noise was determined only with the natural sounds of the cave. It was not possible to do this measurement during the dry season due to logistic reasons and the necessity to keep the caves open to the public. Similarly to what happens in the two previous caves, the main source of noise are the water drops, since there is no other noise source coming from the inside or the outside of the cave. A LA_{eq} of 32 dB was obtained (fig. 5 and table 2), which, although it represents an audible noise, is still a low value.

4.5 - Results Comparison

The comparison between the results obtained in the three caves when there were no visitors, background music or equipments turned on, in rainy period (since that was the only scenario in common in all the three caves) is represented in figure 5. The results obtained in dry weather, without any equipment turned on, are presented in table 2 [4].

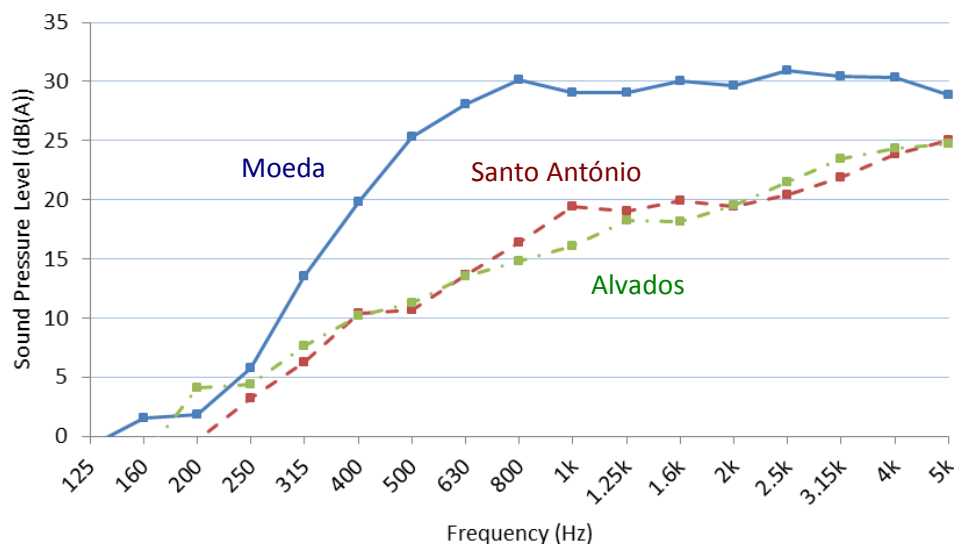


Figure 5 – A weighted sound pressure levels in each cave, in the "no visitors, no music and no equipment" scenario (nS).

Figure 5 shows that *Moeda Caves* have the most significant amount of noise during the rainy weather, with the constant water flow as its main source. The water infiltrations in rainy weather are very significant in all three caves, leading to constant noise of water drops, causing the sound

level in high frequencies to rise. This can be harmful to some types of activities that require a low sound level of the background noise. Even so, even during this period, the background noise has a considerably low sound level, with a mean value of LA_{eq} of 34 dB.

Comparing the rainy and the dry periods, the water flow is the main source of background noise in these rooms, since it is responsible for an increase of about 11 to 17 dB(A) in the measured sound level.

5 - RASTI

The *Rapid Speech Transmission Index* (RASTI) was measured in these caves using a B&K 4225 transmitter, a B&K 4419 receiver and a B&K 3361 analyzer. The measurement locations were the same used while measuring the RT [4].

The comparison of the RASTI values measured in each space elicits which of the caves would provide a better speech understanding, which is an extremely important characteristic for guided visits, theater performances or even conferences. The mean values obtained are presented in table 3. The values range from *acceptable* to *good*, which means there is good speech intelligibility in these spaces.

Table 3 – Mean RASTI values in each cave studied.

Cave	Moeda	Santo António	Alvados
RASTI (room avg.)	0.54	0.50	0.57

With a mean value of about 0.54 for the three caves and minimal values close to 0.40 (further from the sound source), it is possible to say that the perception of speech is good in all three caves, given the considerable distance from the sound source that was used during each measurement (up to 28 m). The biggest variation happens in *Moeda Caves*, since their complex morphology causes large intelligibility losses as the receptor is farther from the transmitter. The smallest variation was obtained in *Alvados*, which can be explained by the fact that this is the space where there are fewer obstacles between the transmitter and the receptor. The low value of RT in all three caves also contributes to an increase in speech intelligibility, since there is less overlapping in the sound waves emitted and reflected by the surfaces.

6 – SOUND ABSORPTION COEFFICIENT AND FORM FACTOR

The experimental determination of the sound absorption coefficient of the rock samples collected from the cave's walls was obtained using a standing wave apparatus (B&K 4002, B&K 1024 analyzer and B&K 2231 sound level meter with a 1625 filter) [4].

The results, obtained using this method, are for a 90° incidence of the sound waves to the sample surface. In this case, the exposed surface of the sample in the holder, to the apparatus sound waves is not parallel to the holder surface, because the sample rock was slightly rounded. Consequently, it was assumed that the sample's exposed area was 10% bigger than the area of the transversal section of the equipment measuring tube and the final results were affected with a factor of 0.9 [4].

The real value of the sound absorption coefficient of any material takes into consideration its capacity to absorb sound waves coming from all directions. Although there are some approaches that try to simulate this effect based on the results of the standing wave apparatus, there is no precise method that converts the results of the normal incidence to diffuse incidence, and that can differentiate the results by frequency range. Therefore, in this study the results were not converted to a diffuse incidence.

The samples used in this study were collected in *Moeda Caves*. Sample *I* consists of a low porosity Jurassic limestone rock, and it has some cracks in it. Sample *II* is made of biogenic limestone, originated by the deposition of calcite, with a crystal-type structure. The results obtained are presented in table 4.

Table 4 – Sound absorptions coefficients (α) obtained in the standing waves apparatus to samples I and II (corrected values by a factor of 0.9, to eliminate the increased area of the rounded shape of the sample used).

Frequency band (Hz)	500	1k	2k	4k
α I <i>corrected</i>	0.09	0.08	0.08	0.09
α II <i>corrected</i>	0.07	0.08	0.08	0.09

The values which were obtained experimentally for the sound absorption coefficient of the material (rock) that is in the surfaces of the cave allows one to estimate the real area of the surrounding surfaces of the room, creating an approximation that can be used in similar caves. Therefore, by defining a *form factor* F_f that relates the estimated area of the surrounding surfaces of the room (S_{env}) to the surrounding surfaces area if the surfaces were regular (S_{reg}), and applying Sabine's formula, one obtains (SWA, standing wave apparatus; A_{air} , absorption of the volume of air; A_p , absorption of three persons):

$$F_f = \frac{S_{env}}{S_{reg}} = \frac{\frac{0.16V}{T} - A_{air} - 3A_p}{\alpha_{SWA} S_{reg}} \quad (2)$$

After calculating the approximate area of the surface surrounding the cave (in assumed regular shape), and knowing the remaining necessary values, it is possible to calculate the form factor (F_f) as in table 5 (from expression 2). Therefore, the real surrounding surface area in each cave is about 2.2 to 2.8 times superior as if in a regular shaped room, due to the complex geological and karst formations (stalactites, stalagmites, etc.).

Table 5 – Estimated area of the room surfaces if they were regular (S_{reg}), of the real area of the surfaces including the karst formations (S_{env}) and of the form factor (F_f) for each cave.

Cave	S_{reg} (m ²) app.	S_{env} (m ²) app.	F_f ($= S_{env} / S_{reg}$)
Moeda	1650	4620	2.8
Santo António	3700	10360	2.8
Alvados	850	1870	2.2

7 – CONCLUSIONS

The *Moeda*, *Santo António* and *Alvados* caves are representative of many other caves of karst formation globally. Therefore, the results obtained in this study can be used as a reference for studying spaces with similar geological origin and morphological characteristics.

The results of the *in situ* measurements, with mean RT (500/1k) values ranging from 1.3 to 1.7 s and RASTI values ranging from 0.50 to 0.57, indicate surprising acoustic characteristics, with a very low reverberance considering the volume and the material that constitutes the surfaces of the walls. The caves are spaces with low RT and good intelligibility due to the complex structure and the morphology of their walls, which, besides diffusing and dissipating the sound energy, constitute a large absorption area. The values of the *LAeq* background noise obtained on rainy weather (32 to 40 dB) correspond to an audible but pleasant sound level. The results obtained in dry weather, of 22 to 23 dB (with $LA_{90} < 20$ dB) show that these spaces are really silent. The caves can be easily adapted to be used for other activities besides guided visits. Table 6 compares the measured values with those considered ideal for certain uses and allow to determine the uses each space is more suitable for.

Table 6 – Suitability of the spaces for each type of use.

Use		Moeda Caves	Santo António Caves	Alvados Caves
Auditorium (speech) or theater		<i>Suitable</i>	<i>Not Recommended</i>	<i>Suitable</i>
Chamber music or opera		<i>Suitable</i>	<i>Excellent</i>	<i>Excellent</i>
Gregorian singing, choir or organ		<i>Not Recommended</i>	<i>Not Recommended</i>	<i>Not Recommended</i>
Symphonic Music	Baroque	<i>Suitable</i>	<i>Suitable</i>	<i>Excellent</i>
	Classic	<i>Suitable</i>	<i>Excellent</i>	<i>Suitable</i>
	Romantic	<i>Not Recommended</i>	<i>Suitable</i>	<i>Suitable</i>

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